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A New Space Vector Approach to Detect Stator Faults in Induction Motors

K. N. Gyftakis and A. J. Marques Cardoso

Abstract – Although induction motors are robust devices, faults may appear and so reliable and stable operation is required. More aspects need to be addressed nowadays in terms of condition monitoring. It is necessary to extract as much information as possible related to the overall motor condition and health. Also, different levels of diagnosis are required, as well necessity of detecting the fault level severity and avoiding false positive/negative alarms. This paper presents a new method to detect stator inter-turn faults in induction motors using a new space vector approach. This new vector is based on the higher harmonic index of the Park's Vector. It is revealed that the time-representation of this vector offers a reliable diagnostic alarm. Moreover, the frequency spectrum of the proposed vector's modulus can be studied and analyzed to extract more information regarding the fault level severity.

Index Terms—Condition Monitoring, Fault Diagnosis, Finite Element Method, Induction Motor, Stator Fault.

I. INTRODUCTION

DEPENDING on the induction motor size and power, different motor components present various degradation mechanisms. Among them, the stator faults account for about 30% in medium voltage induction motors while, the percentage increases to 66% in large high voltage ones [1].

Stator faults can be classified in three main groups: iron core faults [2], electrical/insulation faults [2] and wedges faults [3]. The most usual stator fault is the inter-turn fault. It is caused by the progressive degradation of the windings insulation material. This degradation is caused by the well-known TEAM (Thermal, Electrical, Ambient and Mechanical) stresses [4]. The insulation degradation leads to altering the chemical composition or deterioration of the insulation material. As a result, a short circuit between conductors of the same phase is created. Typically, the inter-turn fault evolves fast into a catastrophic motor failure. It was reported than in small machines this time is less than a minute [5].

Due to the serious consequences of stator inter-turn faults, much work has been accomplished in the past aiming to the reliable detection of stator inter-turn faults at an incipient stage. Current-based methods have been the most popular. It was proposed in [6] to use the negative sequence current as a diagnostic mean. Moreover, other transforms of the stator current such as, the Park's Vector Approach [7], the Extended Park's Vector Approach [8], the stator current

envelope [9], the stator current in multiple reference frames [10]-[11], the zero-sequence current [12] and the wavelet transform of the stator current [13]-[14] have also been used as reliable diagnostic means.

Other electromagnetic variables such as power and torque [15]-[16] have also been used. In [17] the pendulous oscillations phenomenon is investigated. More recently, it was proposed to reliably detect and distinguish the stator inter-turn fault from other asymmetrical operating characteristics by the use of the active and reactive power harmonics index [18].

This paper introduces a new space vector approach to address the stator inter-turn fault detection at an early stage. The method relies on the well-established Park's Vector Approach (PVA). However, instead of using the original d and q stator current components, the method takes advantage of their higher harmonic index. The method was used with success in the past for rotor electrical faults detection [19]. This is the first time that it is applied for stator faults. The performed work, has been carried out with Finite Element Analysis. The results prove the method's simplicity, reliability and effectiveness, as well its distinct advantage over the traditional Park's Vector Approach.

II. THE FINITE ELEMENT MODEL

The work has been carried out with Finite Element Simulations. The studied model takes its geometrical and materials' characteristics from a 400 V, 4 kW, 50 Hz, 3-phase squirrel cage induction motor. The stator slot number is 36 and the rotor slot number 28. Due to the long simulations in order to acquire steady state signals appropriate for signal processing, the simulated models have been analyzed in 2D, thus without skewing.

Six different models have been created and studied: the healthy and 5 more with a stator inter-turn fault. The faulty motors have 1%, 2%, 3%, 4% and 5% fault severity. The fault severity has been calculated as a percentage of the shorted turns over the total number of turns of the faulty phase. A cross section of the faulty motor model is shown in Fig. 1. The arrows point at the location of the phase turns influenced by the fault. Moreover, the short circuit creation is shown in Fig. 2 to determine the resulting circuit. The number of wires in each slot has been divided in three groups. The first and last slot have k, l and a single wire. Moreover, the inner slots have m, n and a single wire. If A and B points are short circuited, then k+1, n, n+1 and k wires in the four slots respectively continue to be part of the phase. Naturally, the remaining wires form the short circuit loop.

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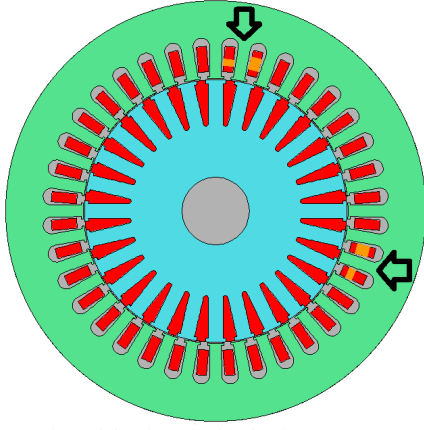


Fig. 1. A cross section of the simulated induction motor.

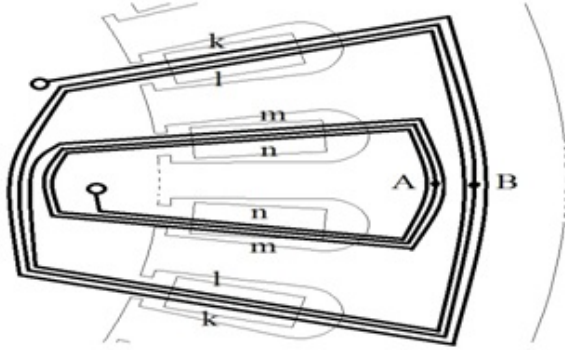
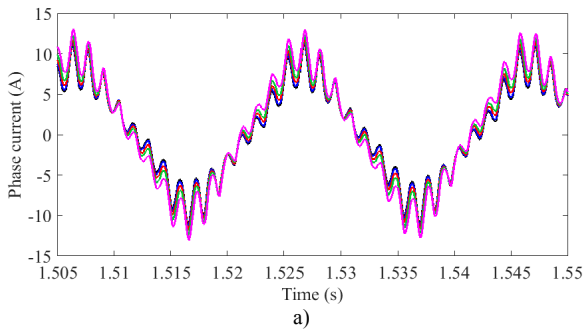


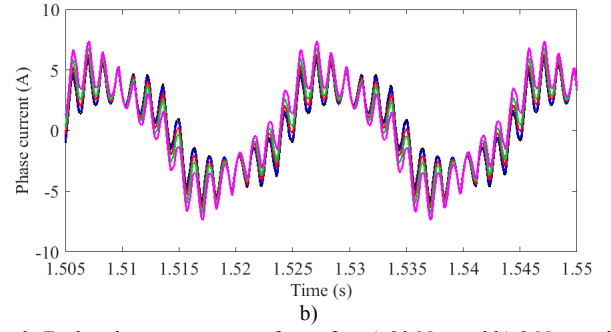
Fig. 2. Wires distribution to account for the inter-turn short circuit fault.

The faulty phase current waveforms for all severity levels are shown in the following Fig. 3 for rated load (30 Nm) and low load operation (3 Nm). It can be seen that the fault level severity does not have a strong influence on the faulty phase current. This is due to the small phase resistance decrease (only 1%-5%) when the fault occurs.

On the other hand, the current waveforms flowing in the shorted turns of each case are illustrated in Fig. 4. As expected, the increase of the short current amplitude with the fault severity is monotonic and approximately linear. Interestingly, the amplitude of the short current appears independent from the applied mechanical load. This is due to the mechanism creating the short current. The shorted turns are static over time thus, voltage is induced due to the rotating magnetic field according to Faraday's law of induction. Since, the faulty phase current difference is low and the shorted turns number is fixed, the induced voltage is the same independent from the load and as a consequence the short current too.

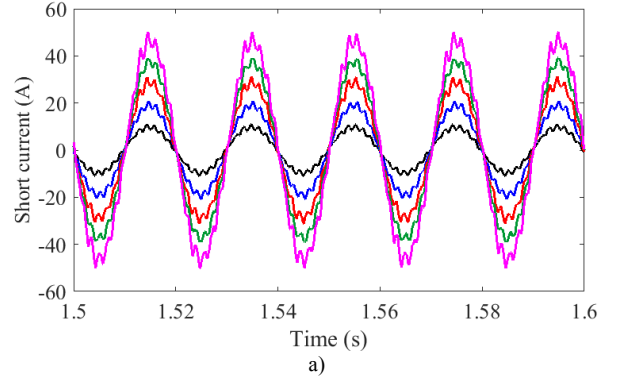


a)

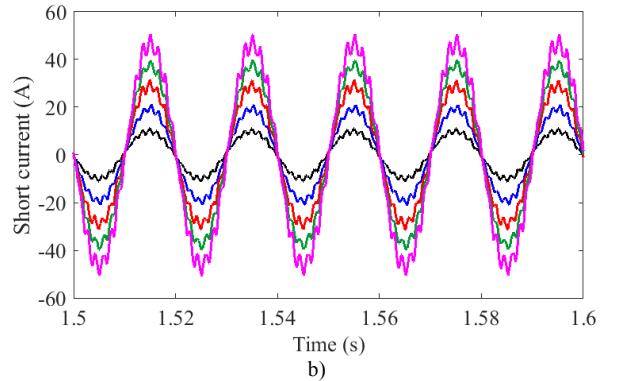


b)

Fig. 3. Faulty phase current waveforms for: a) 30 Nm and b) 3 Nm applied load. Fault severity-colour: 1%-black, 2%-blue, 3%-red, 4%-green and 5%-purple.



a)



b)

Fig. 4. Short current waveforms for: a) 30 Nm and b) 3 Nm applied load. Fault severity-colour: 1%-black, 2%-blue, 3%-red, 4%-green and 5%-purple.

III. ANALYSIS RESULTS AND DISCUSSION

A. Traditional Park's Vector Approach

The traditional PVA relies on the monitoring of the three-phase or line currents of the induction motor namely: i_a , i_b , i_c .

The Park's Vector components, I_d and I_q , are then calculated by:

$$I_d = \left(\frac{\sqrt{2}}{\sqrt{3}}\right)i_a - \left(\frac{1}{\sqrt{6}}\right)i_b - \left(\frac{1}{\sqrt{6}}\right)i_c \quad (1)$$

$$I_q = \left(\frac{1}{\sqrt{2}}\right)i_b - \left(\frac{1}{\sqrt{2}}\right)i_c \quad (2)$$

Under ideal conditions, i.e. for a healthy three-phase induction machine, fed by a direct three-phase sinusoidal voltage supply system, the three phase currents lead to a Park's vector with the following components:

$$I_d = \left(\sqrt{6}/\sqrt{2}\right) I_M \sin(\omega t) \quad (3)$$

$$I_q = \left(\sqrt{6}/\sqrt{2}\right) I_M \sin(\omega t - \pi/2) \quad (4)$$

where:

I_M : maximum value of the supply phase current (A)

ω : angular supply frequency (rad/s)

t : time variable (s)

The corresponding representation of the Park's Vector is then a circular locus centered at the origin of the coordinates. In case of stator asymmetries the circular shape is distorted and becomes an ellipsis.

The Park's vector for healthy motor (blue), faulty with 1% and 5% fault severity (red) is shown in Fig. 5. Due to the normally existing higher harmonic index of the stator phase currents, the locus is not a circle even in the healthy motor. However it is clear that due to the low fault level severity it is difficult to detect the fault. Furthermore, a small distortion can be observed for 5% fault severity. So, although simple and computationally efficient this method lacks of reliability for low severity levels.

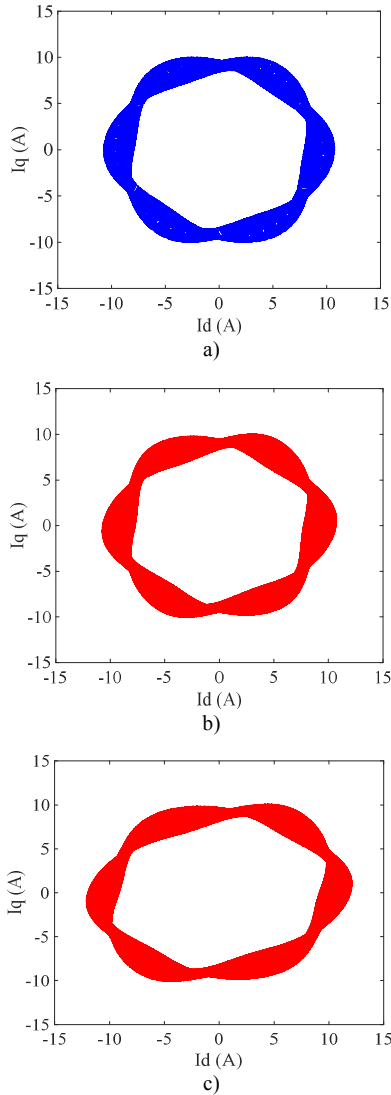


Fig. 5. The Park's vector representation for: a) healthy motor, b) motor with 1% fault severity and c) motor with 5% fault severity, operating under rated load.

B. Proposed Method and Results

The main disadvantage of the traditional Park's vector approach is that it does not offer a significantly different representation between healthy and faulty cases, thus strongly depends on additional further analysis. To overcome this problem, it is important to neglect the impact of the fundamental stator current harmonic, the amplitude of which is much stronger than the ones from the higher harmonic index.

After the computing of both d and q components of the Park's vector, filtering of the two signals takes place in two stages. Firstly, a low pass, elliptic filter is applied to cutoff harmonics higher than 370 Hz. This is important due to the fact that the studied motor is a Principal Slot Harmonic induction motor according to [20]. This means that due to its rotor slot number/magnetic poles number ratio, it produces strong rotor slot related harmonics at higher frequencies. Moreover, no skewing has been considered and as a result those harmonics are somewhat stronger than expected in the real motor.

Afterwards, a Notch filter is applied to subtract the fundamental 50 Hz harmonic. As a result, the d and q components of the Park's vector mainly contain the 5th and 7th harmonics (250 Hz and 350 Hz) in the healthy motor. This can be seen for the d component in Fig. 6. Furthermore, the new representation of the Park's vector can be seen in Fig. 7. It is evidently a Lissajous knot, which consists of a family of ellipsis.

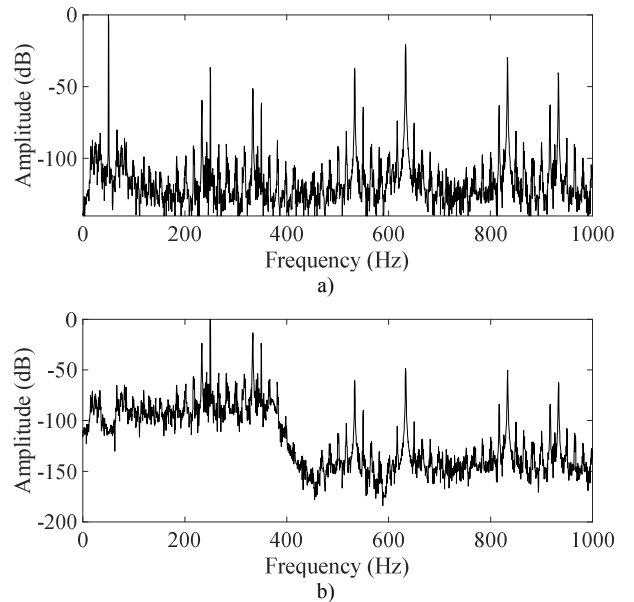


Fig. 6. The frequency spectra of the Park's vector d component: a) before filtering and b) after filtering.

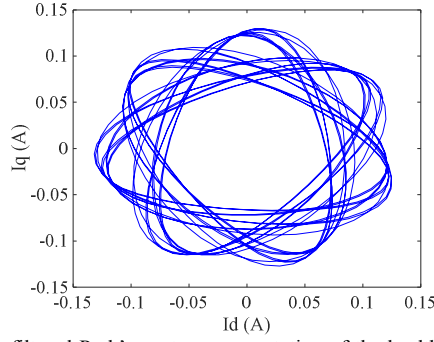


Fig. 7. The filtered Park's vector representation of the healthy motor under rated load operation.

If there is a stator inter-turn fault, the asymmetry between the three phase currents will give birth to even rank harmonics in the d and q components of the Park's vector. Now that the fundamental harmonic is absent, the amplitudes of the even harmonics are comparable to the 5th and 7th normally existing harmonics. Consequently, the Lissajous diagram will be built by two components each of which consists of multiple higher harmonics resulting to a ring where the Lissajous knot is undistinguishable, as well as its lobes.

The above analysis has been applied to all faulty cases and indeed the resulting representation is a ring which slowly becomes elliptic while the fault level severity increases. The results can be seen in the following Fig. 8.

To allow for a second more detailed level of diagnosis, the modulus of the filtered Park's vector is calculated. This is not a random step. A significant past review work [21], which compared different diagnostic methods, illustrated the diagnostic value of the Extended Park's Vector Approach (EPVA). The EPVA relies on the analysis of the original Park's vector modulus spectrum. According to the above mentioned work, EPVA proved to be the second best (among thirteen studied methods) to diagnose rotor electrical faults in induction motors (average of full, medium and low load

operation) and the best option for low load operation.

The modulus waveforms of the filtered Park's vector for motor operation under rated load can be seen in Fig. 9. It can be seen that the fault results to a distortion of this signal. The distortion appears to increase with the increase of the fault severity level. However, for very low severity levels 1% and 2% it is not possible to distinguish the fault severity since the distortion looks the same.

The frequency spectra of the modulus waveforms are shown in Fig. 10 and the various harmonics amplitudes have been gathered and presented in Table I. It is clear that the fault existence leads to the appearance of strong even rank harmonics at 100 Hz, 200 Hz and 400 Hz. Those harmonics are absent in the healthy motor. Furthermore, rotor slot related sidebands are observed around the even harmonics ($\pm f_{rs}$). Interestingly, most harmonics do not present a monotonic increase with the increase of the fault severity. Only when the fault severity is 5% all harmonics appear to significantly rise with respect to other severity levels. This could be due to non-linearity of the iron core and the impact of local saturation.

IV. CONCLUSIONS

This paper deals with stator inter-turn faults in induction motors using FEM simulations. A new vector based on the higher harmonic index of the d and q components of the Park's vector is proposed for reliable diagnosis. The results illustrate the method's effectiveness and superiority over the traditional Park's vector approach even for low severity levels. The fault related signatures in the modulus of the filtered Park's vector have also been analyzed and lead to the conclusion that the fault severity level is not easily determined at low severity levels. More work is required to this direction aiming for analyzing the impact of local iron core saturation on the production of those harmonics.

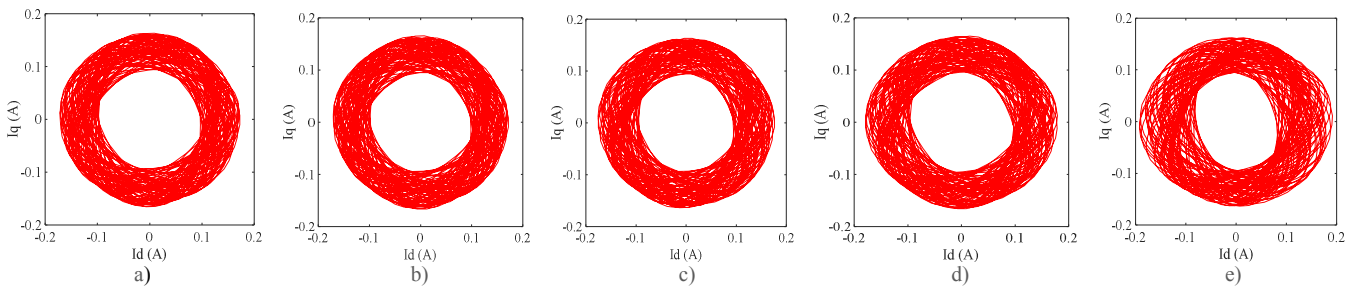
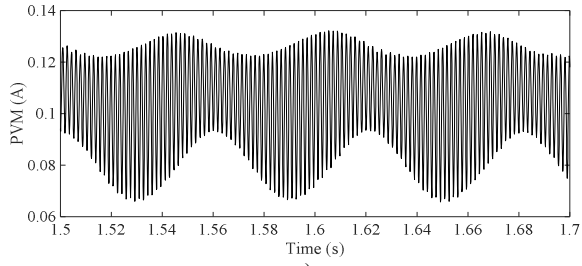


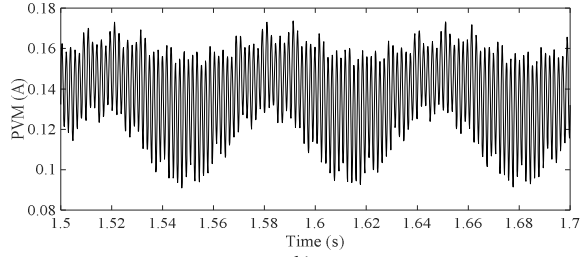
Fig. 8. The filtered Park's vector representation of the faulty motors under rated load operation: a) 1%, b) 2%, c) 3%, d) 4% and e) 5% fault level severity.

TABLE I
HARMONICS AMPLITUDES OF FAULTY MOTORS CASES UNDER RATED LOAD (dB)

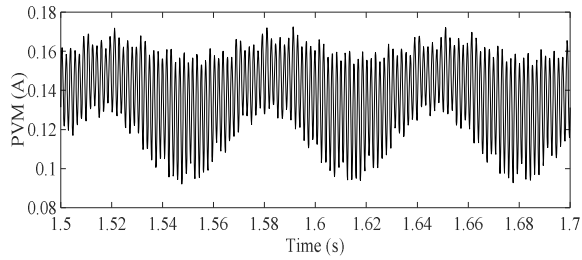
Frequency (Hz)	100 - frs	100Hz	100 + frs	200 - frs	200	200 + frs	400 - frs	400	400 + frs
Severity 1%	-51.99	-38.46	-63.81	-87.11	-59.49	-68.59	-66.3	-38.76	-69.78
Severity 2%	-56.13	-41.94	-65.65	-86.84	-60.07	-69.23	-65.32	-39.08	-69.79
Severity 3%	-43.37	-35.64	-61.82	-83.62	-59.78	-71.09	-64.2	-39.9	-72
Severity 4%	-42.94	-35.47	-62.68	-78.95	-56.57	-66.75	-59.18	-36.63	-71.1
Severity 5%	-34.73	-27.3	-57.91	-72.34	-52.87	-65.33	-54.86	-35.09	-75.64



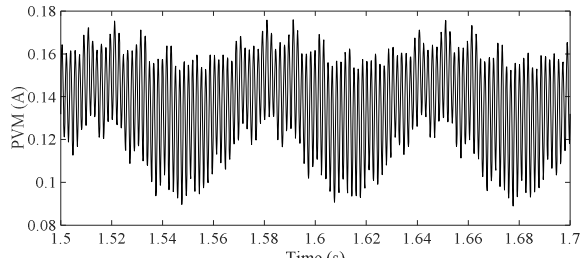
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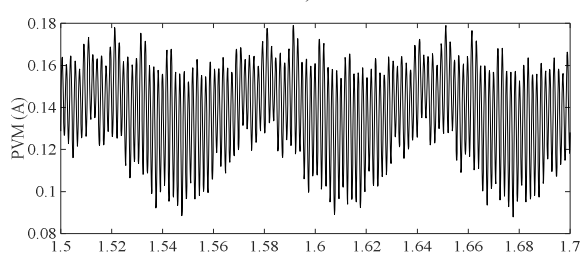
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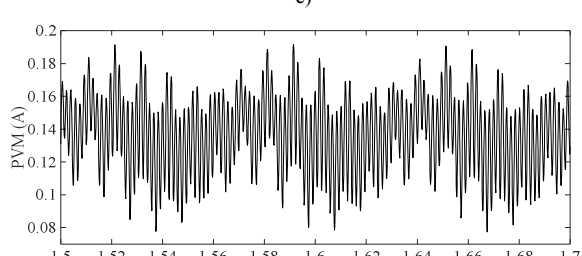
c)



d)

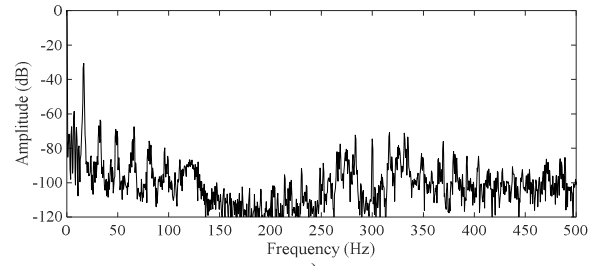


e)

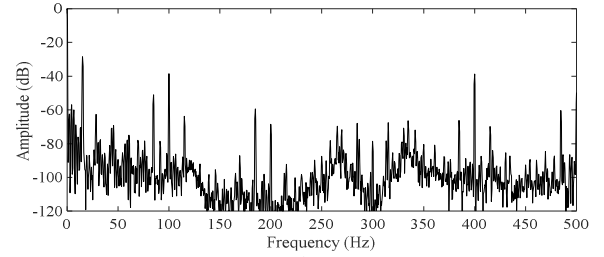


f)

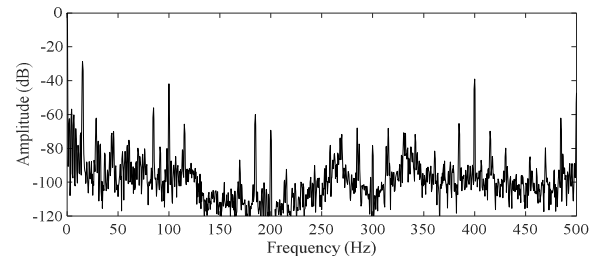
Fig. 9. Waveforms of the filtered Park's vector modulus for: a) healthy, b) 1% fault severity, c) 2% fault severity, d) 3% fault severity, e) 4% fault severity and f) 5% fault severity.



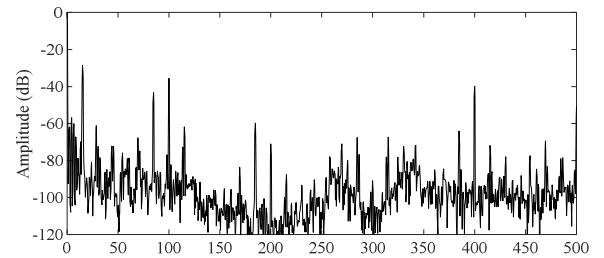
a)



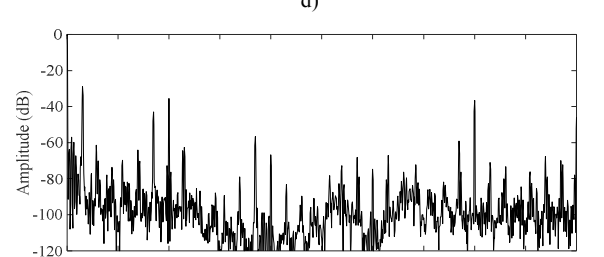
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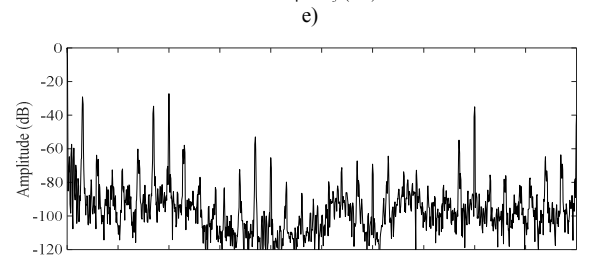
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d)



e)



f)

Fig. 10. Spectra of the filtered Park's vector modulus for: a) healthy, b) 1% fault severity, c) 2% fault severity, d) 3% fault severity, e) 4% fault severity and f) 5% fault severity.

ACKNOWLEDGEMENT

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VI. BIOGRAPHIES

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Antonio J. Marques Cardoso (S'89, A'95, SM'99) received the Dipl. Eng., Dr. Eng., and Habilitation degrees from the University of Coimbra, Coimbra, Portugal, in 1985, 1995 and 2008, respectively, all in Electrical Engineering. From 1985 until 2011 he was with the University of Coimbra, Coimbra, Portugal, where he was Director of the Electrical Machines Laboratory. Since 2011 he has been with the University of Beira Interior (UBI), Covilhã, Portugal, where he is a Full Professor at the Department of Electromechanical Engineering and Director of CISE - Electromechatronic Systems Research Centre (<http://cise.ubi.pt>). He was Vice-Rector of UBI (2013-2014). His current research interests are in fault diagnosis and fault tolerance in electrical machines, power electronics and drives. He is the author of a book entitled *Fault Diagnosis in Three-Phase Induction Motors* (Coimbra, Portugal: Coimbra Editora, 1991), (in Portuguese) and of around 400 papers published in technical journals and conference proceedings. He serves as Guest Editor of the *IEEE Transactions on Industry Applications* Special Issue on *Fault Diagnosis of Electric Machines, Power Electronics and Drives* and Associate Editor for the *IEEE Transactions on Industry Applications*, *IEEE Transactions on Industrial Electronics*, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, and also for the Springer *International Journal of Systems Assurance Engineering and Management*.